MEASUREMENT OF OCEAN SURFACE IN SHOALING ZONES BY LASER ARRAY AND Ka-BAND RADAR*

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ABSTRACT

Integration of airborne high-frequency GPS with laser altimetry and a Ka-band radar scatterometer provides a versatile new measure of water-wave structure, especially over shallow water with complex bottom topography. Unaffected by sea state or water depth, an airplane can observe the sea surface shape over the transition near shore. Three laser altimeters are mounted in a nominally equilateral triangle with 1-m sides, aimed perpendicular to a reference plane defined by the airplane's attitude system. The lasers measure the height and slope of the sea surface on scales of at least a few meters. The slope helps determine the waves' orientation, hence their actual wavelength and propagation velocity. The 2 kHz pulse rate provides redundant sampling since individual readings depend on striking a properly oriented facet of the water surface. Normal data loss is 1 - 2%, except on calm days, fortunately less interesting. A 36 GHz radar complements the laser array, sampling ocean backscatter from waves within a meter-diameter footprint. Thus the full system measures the sea surface from the smallest capillary waves to multiple kilometers and fits on a small, inexpensive airplane. The GPS-based navigation system achieves at least ± 0.2 m in the vertical and ± 0.06 deg in attitudes.

1.0 INTRODUCTION

Detailed knowledge of the state of the sea surface has been found important in a number of engineering and scientific applications from interest in the effect of water waves on structures and beaches to the influence of the wave shape on the return of signals from satellites. The ocean's surface is one of the great interfaces on our planet across which the transfer of mass, momentum, and energy determines how these quantities will be distributed over the earth and what the earth's climate will be.

Measurements of the sea state have traditionally been made from watercraft and fixed platforms. These have advantages of being able to remain on station for long periods of time and to measure turbulence in the water as well as in the air. They are, however, subject to minimum or maximum constraints on water

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depth. Moreover, towers and platforms are constrained in location, while watercraft may be tossed about in strong waves, especially where deep ocean water meets the shallows. It is only recently that technology has allowed practical exploitation of an airplane's complementary features of mobility independent of water depth and relative independence of sea state.

Fundamental to this advance has been the ability to determine the airplane's location to high precision, accuracy and frequency. Knowing the airplane's position allows determination of the shape of the water surface by laser rangefinder or by microwave scattering. As with many remote-sensing applications, the Global Positioning System, coupled with modern high-speed portable computers has made this possible. As satellite-based navigation continues to advance, the cost of these systems decreases even as the accuracy increases.

2.0 DESCRIPTION OF SYSTEM

Recent advances in GPS technology provide the ability to determine very accurately the position, velocity, and orientation of quite small vehicles. The airplane used in this application is nearly ideal for high-fidelity measurements of atmospheric turbulence and readily capable of flight at low speeds and altitudes appropriate to precision measurement of the sea state. The relatively small weight and power of the airplane provide minimal disturbance of the environment in which the measurements are taken. The pusher configuration places the greatest sources of disturbance, wings and engine, behind the main points of measurement. The airplane is well suited to a combination of in-situ atmospheric turbulence measurements and remote sensing of the shape of the sea surface (Crawford *et al.*, 1996; Crawford and Dobosy, 1997).

Remote sensing of the sea state is by two techniques. Three laser range finders measure directly the distance between the airplane and the instantaneous sea surface. These near-infrared lasers (905 nm) consume 45mW on average (class 3B), delivering a 20ns pulse twice per millisecond to a spot on the surface approximately 45mm by 7.5 mm, assuming 15 m altitude. Forty pulses are averaged, providing fifty samples per second, or about one per meter of travel. The forty-fold oversampling reduces the variance among individual measurements and minimizes loss of data. Generally 98% or more of the 50 samples are recovered each second. The system relies on specular reflection and is more reliable when the water surface is dimpled by capillary waves, raising the probability that pulses will strike a wave facet properly oriented to return the signal to the detector. On calm days, swell tilts the surface sufficiently that the return signal can miss the detector up to half the time. Fortunately such days are of considerably less interest than days with waves.

The airplane was fitted with a downward-looking low-power (20 mW) Ka-band (36GHz, 8.3mm wavelength) continuous-wave radar. Its footprint is about 1 m in diameter at the nominal flight altitude of 15 m. The band was chosen to meet size requirements. As with the lasers, radar return depends on specular reflection from the water surface. The larger footprint, however, makes the radar much more tolerant of small swell-induced changes in angle. Strongest return is from a flat surface. Small waves within the footprint will reflect some of the signal away from the receiver. Thus the power returned from a nadir-aimed radar antenna is inversely proportional to the variance of the slope due to small waves within the footprint, and to the tilt, due to longer waves, of the underlying surface facet.

The radar scatterometer is mounted in a pod beneath the centerline of the fuselage. The lasers are arrayed in an approximate equilateral triangle with sides of about 1 m. Two are mounted in the strakes at the roots of the wings; the third is in the pod that contains the radar. Although the plane defined by the three lasers is not “horizontal” (quotation marks will refer to airplane coordinates), the positions of the lasers are precisely known, relative to the origin of the airplane’s coordinate system. The lasers are set as nearly parallel as possible and directed normal to the airplane’s “horizontal” plane.

In addition to the remote sensing of the sea surface, the airplane is equipped for *in-situ* measurement of atmospheric turbulence: winds, temperature, moisture, and CO_2. The turbulence instruments are co-located in a probe, designed in a collaboration between ATDD and Airborne Research Australia. This probe differs from the usual gust probe in that it also carries temperature sensors, a GPS antenna and accelerometers. Thus the position and motion of the probe can be determined directly. Also the temperature, measurement, being located within a pressure-sensing port can be readily corrected for compression heating. This design has been demonstrated to provide high fidelity, high frequency measurements of turbulent motions at considerably lower cost than for many other airborne systems. (Crawford *et al.*, 1996, Dobosy *et al.*, 1997).

3.0 DATA HANDLING

3.1 POSITION AND ATTITUDE OF AIRPLANE

Fundamental to an accurate determination of the height of the waves is accurate knowledge of the position and attitude of the airplane: six independent measurements, 50 times per second. The backbone of our system is the Global Positioning System. We have been keeping current with developments in commercially available receivers for ten years. Although the units we currently use are considerably more expensive than the simplest GPS receivers available, they still cost far less than comparable capability based on an inertial navigation system. Furthermore opportunities for improvement in GPS techniques remain, and the cost of the receivers continues to drop.

The accuracy requirements demand differential correction, the technique by which errors, particularly Selective Availability, common to two receivers in the same area are removed by subtraction. The most accurate differential correction technique compares the phases of the carrier waves acquired by the two receivers from multiple satellites. By this technique we have achieved 0.2 m accuracy in our vertical positions over time. The result can be improved by dual-frequency receivers, which receive GPS signals from both broadcast frequencies. Without military access a receiver can obtain from the military frequency L2, only the phase of the carrier. Still this information allows determination and account of the influence the ionosphere has on propagation of the signal.

The airplane’s velocity, important to accurate wind and turbulence measurements is determined from GPS by sensing the Doppler shift in the carrier waves from the satellites. Relative motions between a receiver and at least four satellites allow determination of the velocity of the receiver, along with its time offset.

The airplane’s attitude can also be measured by GPS, essentially again an application of precision position measurements. Our system has four antennas mounted in a cruciform pattern, fore, aft, and on each wing. The single-frequency receiver computes carrier-phase differential correction providing orientation information to about 0.1 degrees of arc.

These GPS antennas have been placed on the airplane to optimize the measurement of the attitude and velocity of the turbulence probe. Indeed the origin of the airplane’s coordinate system resides in the probe. The lasers and radar, being away from the origin, undergo linear displacement due to rotation of the airplane about its origin. A proper description of the position of the lasers and radar thus requires knowledge of the airplane's attitude as well as the position of its origin.

Our GPS receivers report ten times per second. These instantaneous measurements contain a significant amount of noise and are greatly improved by averaging. Furthermore, ten readings per second is insufficient by a factor of five. Acceleration measurements at several locations over the airframe provide the necessary extension.

High-frequency orientation is obtained from differences of acceleration. The difference between vertical accelerations on each wing, twice integrated, provides the high-frequency roll angle. A similar difference fore and aft provides pitch, while a difference between lateral accelerations fore and aft gives, yaw. These double integrations may extend over several seconds before measurement errors accumulate unacceptably. This allows GPS attitudes to be averaged over at least a second, greatly reducing their noise. The hybrid system reports accurate attitudes at all frequencies up to 25 Hz, the Nyquist frequency of the samples.

High-frequency velocity and position are likewise obtained from integrals of acceleration measurements. With accelerometers in the probe, its velocity can be directly measured, contributing to high-fidelity determination of turbulent winds. The position of the lasers at high frequency is likewise directly provided by integration of accelerations measured near the center of the airplane's mass. Thus the airplane's attitude need be considered only for the lower-frequency components of the positions of the lasers and radar, measured by GPS. This simplification greatly benefits accuracy.

3.2 WAVE HEIGHT AND SLOPE

With the absolute height of the airplane determined, the absolute height of the water surface is given simply by subtracting the airplane's instantaneous height above the water. This is directly measured at three locations by the lasers. If the airplane is not vertical, its roll and pitch angles need to be considered in determining its perpendicular distance to the water.

Three lasers also measure a wave slope, without reference to the airplane's height. Since the lasers are not all located in the airplane's "horizontal" plane, each laser's distance reading is adjusted by additive offset to establish a "horizontal" reference plane. The reference plane's location is arbitrary and can be chosen for convenience. The lasers fire normal to this reference plane, projecting it onto the water surface. The normal to the water surface is then the cross product between any two of the three vectors that form the triangle projected onto the water surface (*e.g.* $\mathbf{Z_2Z_1}$ and $\mathbf{Z_2Z_3}$ in Figure 1). This normal vector is, of course, still expressed in airplane coordinates. Rotation to earth coordinates, using the instantaneous roll, pitch, and heading gives the desired slope. This slope is actually that of the secant plane touching the water only at the three

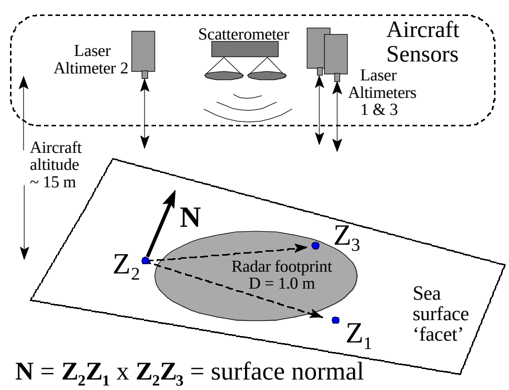

Figure 1. Schematic diagram showing the triangular laser array and the footprint of the Ka-band radar.

points $\mathbf{Z_1}$, $\mathbf{Z_2}$, and $\mathbf{Z_3}$ of figure 1. Surface features smaller than about 1 m can not be described in this way.

Features too small to be explicitly resolved by the laser triangle can be characterized by the radar, using the inverse proportionality between the strength of return and variance of surface slope. The radar's footprint is conveniently about the same size as the laser triangle.

Data handling for the radar consists of converting the measured voltages to normalized radar cross section (NRCS) using the standard radar link equation. This conversion relies on accurate range from the laser altimeters. The system power is monitored in flight and calibrated post-flight. For use as a surrogate for the short-scale sea slope variance only those radar samples are used where the aircraft pitch and roll are less than 2-3 deg. This conditional sampling eliminates any effects from the change of specular scatter with incidence angle.

4.0 APPLICATIONS

This sensor suite has so far been used in measurements on the coast of North Carolina, characterized by Intracoastal Waterway, barrier islands, and continental slope. An illustration of the accuracy of the system is provided by measurements over the Intracoastal Waterway, a relatively sheltered surface. The laser range (airplane to sea) is plotted as negative for visibility. Most of the variation apparent in the wave height is actual waves. There is, on closer examination however, a low-frequency ripple of about ±0.2 m during this flight, where the airplane's altitude varied over more than 10 m. As this paper was being completed, a phase error was discovered in the processing that should explain the larger excursions associated with rapid changes in the airplane's altitude, such as that near 160 s. The large excursion near 240 s is the barrier island with the stronger ocean waves visible beyond it. These measurements support two recent studies: electromagnetic bias and air-sea coupling in coastal regions.

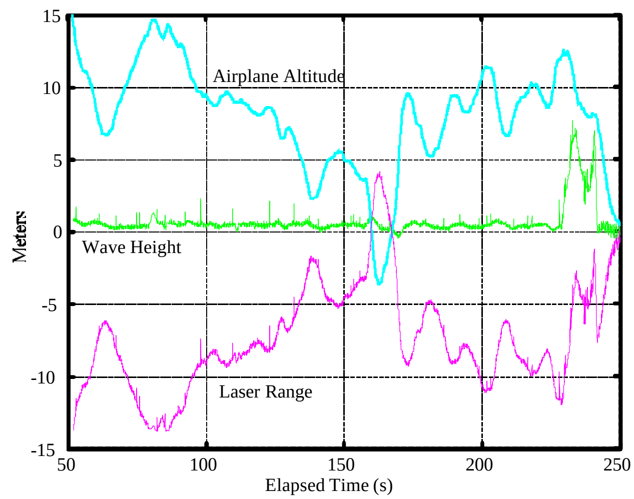

Figure 2. Measurement of Wave Height on 11 November 1997 over the Intracoastal Waterway in North Carolina.

4.1 ELECTROMAGNETIC BIAS IN MEASURED SEA LEVEL

Measurement of large-scale variations in sea level has a number of applications to ocean dynamics and other fields. Accuracies to centimeters are required. Satellites operating radar range finders in the Ku- and C-bands can in principle provide global coverage of the oceans to this accuracy. Ocean waves, however introduce a bias. Since troughs tend to be smoother than crests, the strongest power return comes from the troughs causing mean local sea level to appear lower than it really is. This electromagnetic (EM) bias is a few percent of the significant wave height, hence strong enough to be significant. It depends on the shape of the water waves and on the wavelength of the EM radiation. Wave shape in turn depends mostly on the wind speed, though other factors may also be important, especially in particular settings, such as coastlines or shallows.

Measurements of EM bias require measurement of the wind and wave orientations as well as independent unbiased determination of the height of measurement above the sea. The Long-EZ system provides not only wind, but turbulence measurements, from which momentum transfer to the sea can be determined. The lasers provide independent measure of the height of the sea surface as well as the slope of the significant waves, providing a means to determine the orientation of these waves.

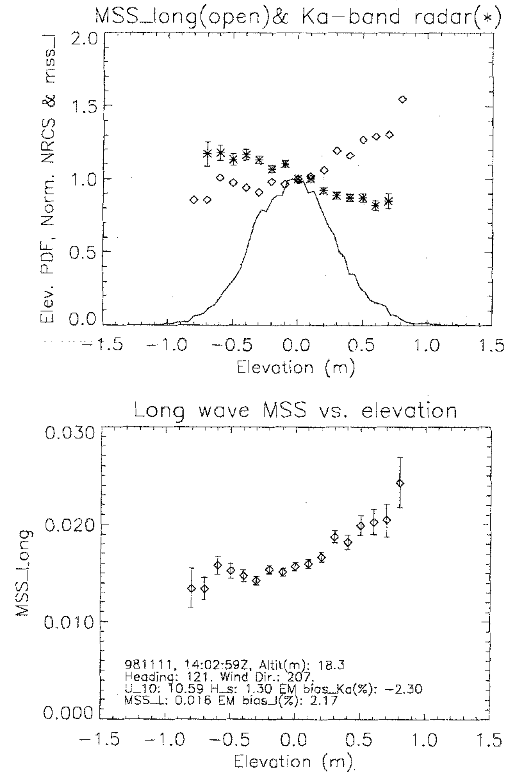

Figure 3. Electromagnet Bias in Local Mean Sea Level. Radar Return (*) from Troughs of Ocean Waves (Negative Elevations) is Stronger Than from Crests.

The nature of the bias is illustrated in the accompanying figure. In the upper panel, the solid line is a histogram of height of the sea surface. Zero is the mean local sea level, while departures are due to waves. The significant wave height (SWH) is taken by convention to be four times the standard deviation of this distribution, which is modeled as Gaussian. The diamonds show the variance of the slope of the sea-surface as a function of elevation of that surface. As is evident in the figure, this variance is lower in the troughs (negative heights) than on the crests of the significant waves. The asterisks show the mean radar cross section, normalized to unity at the mean height. A greater cross section implies stronger return signal. In the troughs, having smoother surface, nearly the entire footprint area reflects signal back to the detector. On the ridges, with stronger variance of slope, a smaller fraction of the surface area reflects radar signal into the detector, hence the smaller effective cross section.

The lower panel shows the adjusted variance of sea surface slope after removal of the contribution from the shortest waves. Spread of the measured values increases toward both the crest and the trough. The shape of the pattern, however, is essentially unchanged from the diamonds above. For this particular day radar estimates of the local mean height of the sea were biased by 2.3%. The Ka-band radar suffers less bias than the Ku-band and C-band radars carried on the NASA TOPEX/Poseidon Satellite. The effect has been found to be nearly linear in wavelength through these microwave bands, however (Arnold et al., 1995), allowing results from the Ka-band measurements to be generalized.

4.2 SURFACE STRESS ON ATMOSPHERE AS FUNCTION OF SEA STATE

Because of the difficulties in measurement and the complexity of the system, the exchange of momentum and heat between the ocean and the atmosphere is still not fully understood. The relation is particularly complex over shallow parts of the ocean, where wave shapes change due to bottom topography, and marine vegetation undergoes strong changes in character.

Over the open ocean, bulk aerodynamic relations are considered acceptable in describing fluxes of momentum, heat, and moisture between air and sea. In such relations momentum fluxes are given as a product of the square of the wind speed with a drag coefficient, while heat fluxes are represented as a triple product of the wind speed, the temperature difference between the air and the sea surface and an exchange coefficient. The drag and exchange coefficients themselves are taken to be functions only of the wind speed, since stronger wind implies larger waves and hence greater roughness. This assumption has come into question even for the open ocean (Donelan *et al.*, 1997), and certainly is suspect on approach to a coastline. Other features of the system, including bottom topography, wave age, and the size and orientation of swell all have been found to have significant influence. Wave age, represented as the ratio of wave phase speed to wind speed is less than unity for "young" waves, for which wind speed is faster than wave speed. It approaches unity for mature waves. Surface roughness is greater for the young waves. Near a shoreline, the reduction in water depth causes an increase in wave height and a reduction in phase speed. One would expect an increase in drag, which is indeed observed in figure 4, taken off the coast of North Carolina in 1997. Though the wind speed decreased (second panel) the surface stress (u*, third panel) remained nearly constant because of the increased drag (first panel). The effect on the exchange of heat and moisture between air and water is not as clearly defined, and the exchange coefficients are not plotted. Air-sea exchange of heat and moisture appear, however, to follow somewhat different rules near the shore than momentum.

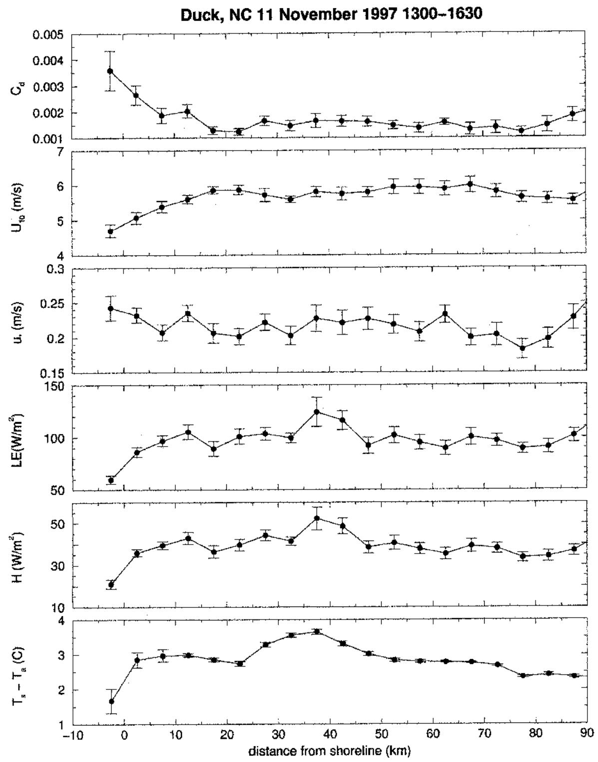

Figure 4. Profiles of Drag Coefficient, Wind Speed at 10 m Above the Sea, Surface Stress Given as Friction Velocity, Latent Heat Flux, Sensible Heat Flux, and Temperature Difference Sea Minus Air.

The system we have developed, largely made possible by advances in GPS and computing technology, combines remotely sensed sea state with *in-situ* measurement of atmospheric turbulence in a small, relatively inexpensive mobile package that significantly expands the ability to explore the air-sea boundary.

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